An Overview of Soil Models for Earthquake Response Analysis

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Abstract. Earthquakes can damage thousands of buildings and infrastructure as well as cause the loss of thousands of lives. During an earthquake, the damage to buildings is mostly caused by the effect of local soil conditions. Depending on the soil type, the earthquake waves propagating from the epicenter to the ground surface will result in various behaviors of the soil. Several studies have been conducted to accurately obtain the soil response during an earthquake. The soil model used must be able to characterize the stress-strain behavior of the soil during the earthquake. This paper compares equivalent linear and nonlinear soil model responses. Analysis was performed on two soil types, Site Class D and Site Class E. An equivalent linear soil model leads to a constant value of shear modulus, while in a nonlinear soil model, the shear modulus changes constantly, depending on the stress level, and shows inelastic behavior. The results from a comparison of both soil models are displayed in the form of maximum acceleration profiles and stress-strain curves.

Keywords: *linear equivalent; nonlinear; soil model; earthquake; wave propagation.*

1 Introduction

Earthquakes causing destruction to thousands of buildings and infrastructure (Figure 1) is inevitable. The impact of this natural disaster, however, can be mitigated. The evaluation of soil response is one of the important issues addressed in the analysis of earthquake geotechnics. Ground response analysis is used to predict ground responses in developing earthquake response spectrum designs. In addition, Kramer [1] explains that earthquake response analysis can also be used to evaluate the dynamic stress-strain of the soil in evaluating liquefaction hazards and to determine the earthquake-induced instability of slopes and earth-retaining structures.

In seismic wave propagation analysis, the actual stress-strain behavior of the soil during an earthquake must be modeled accurately. The results will be used

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as input in designing earthquake resistant buildings. Thus, the loss of infrastructure and lives can be reduced.

The equivalent linear soil model is an approach to model the nonlinear characteristics of the soil. The soil model introduced by Schnabel, *et al.* [2] is much simpler and easier to implement in a computer program. However, it is not able to represent the changes in soil stiffness that actually occurs during an earthquake.

Figure 1 Buildings collapsed during the earthquake in Banda Aceh, 26th of December, 2004.

Nonlinear soil models can represent nonlinear soil behavior better than equivalent linear soil models. The limitations and advantages of equivalent linear and nonlinear soil models were evaluated in this study using several case studies of Site Class D and Site Class E soil types. Acceleration values and the resulted stress-strain values are shown in the form of maximum acceleration profiles and stress-strain curves.

2 The Soil Model in 1-Dimensional Seismic Wave Propagation

2.1 The Equivalent Linear Soil Model

Schnabel, *et al.* [2], Idriss and Sun [3] and Kramer [1] explicate that the actual nonlinear hysteretic behavior can be approached by an equivalent linear approach. The linear approach uses the value of equivalent shear modulus (G) and the equivalent linear damping ratio (ξ). SHAKE is one of the computer programs that first used the equivalent linear approach. In 1998 the computer program EERA (Equivalent-linear Earthquake site Response Analysis) was developed by Bardet and Lin [2], written in FORTRAN 90 and based on the same concept as SHAKE. The input and output used in this program is MS Excel entirely.

The equivalent linear model approach is implemented by modifying the Kelvin-Voigt model to account for some types of soil nonlinearities. The nonlinear and hysteretic stress-strain behaviors of the soil are approximated during cyclic loading as shown in Figure 2.

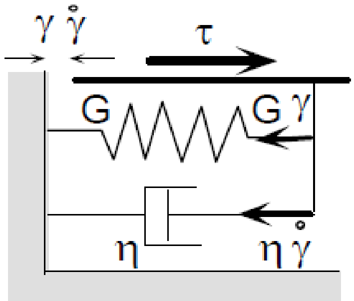

Figure 2 The stress-strain modeling scheme used in an equivalent linear model (after Bardet and Lin [4]).

The equivalent linear shear modulus (G) is taken as a secant shear modulus (G_s) depending on the amplitude of the shear strain (γ_c). As shown in Figure 3a, G_s at the end of symmetric strain cycles is:

$$G_s = \frac{\tau_c}{\gamma_c} \tag{1}$$

where τ_c and γ_c are the shear stress and strain amplitudes, respectively. The energy dissipated (W_d) during a complete loading cycle is equal to the area generated by the stress-strain loop, namely:

$$W_d = \oint_{\tau_c} \tau \, d\gamma \tag{2}$$

The maximum strain energy stored in the system is:

$$W_S = \frac{1}{2}\tau_c\gamma_c = \frac{1}{2}G\gamma_c^2 \tag{3}$$

The critical damping ratio (ξ) can be stated in W_d and W_s:

$$\xi = \frac{W_d}{4\pi W_s} \tag{4}$$

The damping ratio for the equivalent linear model (ξ) is the damping ratio producing the same energy loss in a single cycle as the actual hysteresis stress-strain loop in irreversible soil behavior.

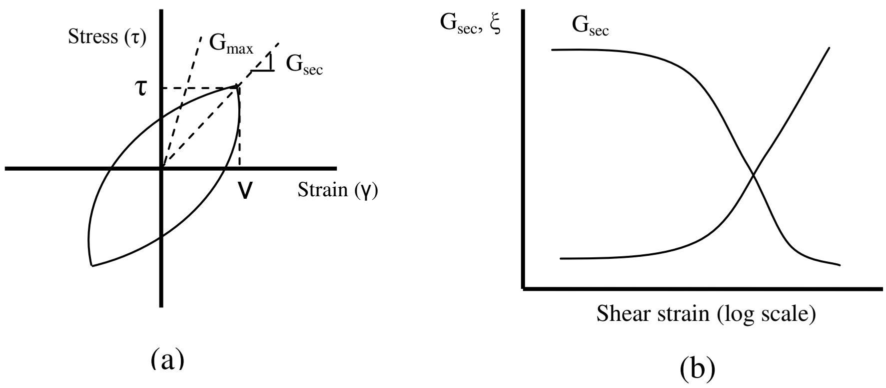

Figure 3 The equivalent linear model: (a) the hysteresis stress-strain curve; (b) the variation of secant shear modulus and damping ratio with shear strain amplitude (after Kramer [1]).

2.2 The Nonlinear Soil Model

There is a wide variety of cyclic nonlinear soil models that have been developed with the characteristics of a hyperbolic backbone curve and also some rules in developing the unloading-reloading behavior, the decrease of stiffness, and other effects have been used. The hyperbolic backbone curve is shown in Figure 4. G_{max} and τ_{max} can be obtained from measurement, computation, or from empirical correlations.

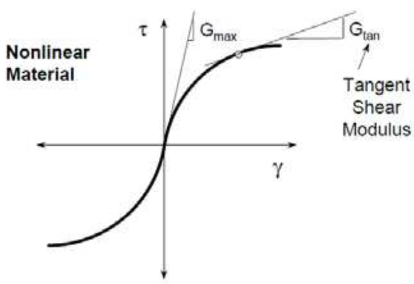

Figure 4 Hyperbolic backbone curve (after Lee and Finn [5]).

Some models using the principle of unloading-reloading, as quoted by Kramer [1], are the Ramberg-Osgood model (studied by Streeter, *et al.* [6]), the hyperbolic model (studied by Lee and Finn [5]), the Martin-Davidenkov model (studied by Martin and Seed [7]), the Iwan type model (studied by Jyner [8]) and the HDCP model (Hardin-Drnevich-Cundall-Pyke, studied by Pyke [9]). Another unloading-reloading model is the multisurface hyperplasticity model [10]. All of these models can be implemented in a ground response analysis.

In the unloading-reloading response of a cyclic nonlinear model, shear strain will not be zero when shear stress is zero. This is the superiority of the cyclic nonlinear model compared with the equivalent linear model. Besides, the ability to calculate the change in pore pressure and also the effective stress changes seems to be superior in the cyclic nonlinear approach. When the pore pressure increases, the effective stress decreases and therefore the value of G_{max} and τ_{max} will decline. The shape and position of the hyperbolic backbone curve depend on the values of G_{max} and τ_{max}. The arch of the curve will decrease as the pore pressure increases.

3 Case Studies

Analysis of wave propagation was performed on two types of classified sites, Site Class E (loose sand and soft clay), and Site Class D (dense sand and stiff clay), using the EERA computer program (Equivalent-linear Earthquake Response Analysis) and the NERA computer program (Nonlinear Earthquake Response Analysis), both developed by Bardet and Tobita [11]. EERA is a computer program applying the basic concept of the equivalent linear model of Kelvin-Voigt (Kramer [1]). To highlight the influence of the input motion on the seismic response of the soil layer, data sets from two existing earthquakes were considered: the earthquake of Duzce (Turkey), representing short distance earthquakes, and the earthquake of Northridge, representing long distance earthquakes.

The first data set is the WE component of the accelerometer registration at Lamont 1061 Station for the earthquake of Duzce (Turkey) on 12th November 1999, denoted as DUZCE/1061-E. The horizontal peak acceleration, equal to 0.134 g, was reached at time t = 17.59 s. The earthquake had magnitude M = 7.14 and distance R = 11.46 km, which classifies as a short distance earthquake.

The second data set is the WE component of the accelerometer registration at CDMG 13660 Station for the earthquake of Northridge on 17th January 1994, denoted as NORTHR/HEM000. The horizontal peak acceleration, equal to 0.064 g, was reached at time t = 24.85 s. This earthquake had magnitude M = 6.69 and distance R = 144.71 km, which classifies as a long distance earthquake. The acceleration time-history and the response spectrum are plotted in Figure 5.

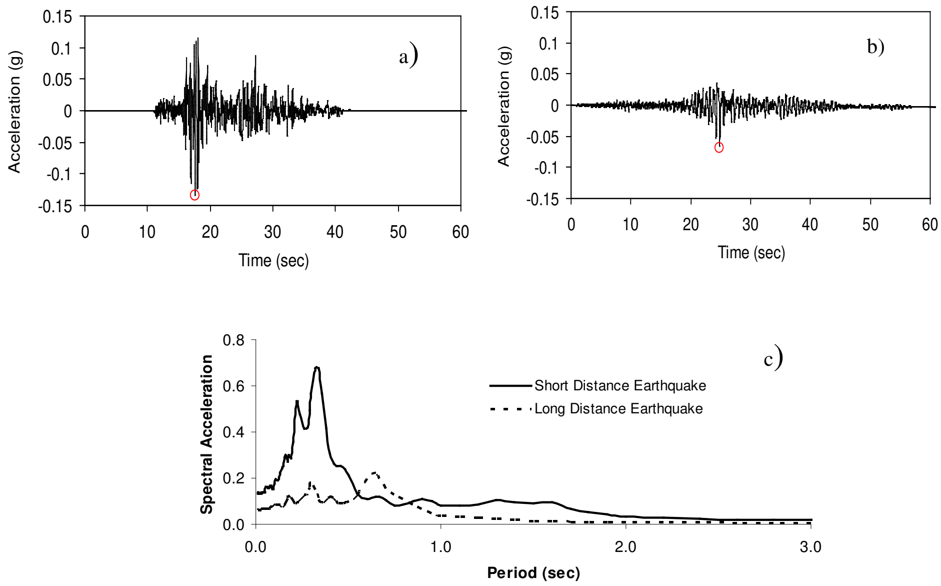

Figure 5 Seismic input signals: a) DUZCE/1061-E acceleration time-history; b) NORTHR/HEM000 acceleration time-history; c) response spectrum.

The peak ground acceleration (PGA) of these two earthquakes was scaled up to 0.3 g, 0.4 g, 0.5 g and 0.6 g. The PGA was scaled up to highlight the effects of the ground motion amplitude on the response of the surface clearly.

3.1 The Case of Site Class E Soil (Homogeneous Loose Sand)

The Site Class E soil (loose sand) profile represented in Figure 6 was analyzed using an equivalent linear soil and a nonlinear soil model. The input ground motion used had a maximum acceleration of 0.134 g for the short distance earthquake and 0.064 g for the long distance earthquake.

The results of the ground response analysis are shown in an acceleration-depth curve (Figure 7) and a stress-strain curve (Figure 8).

Figure 7 shows that the value of the acceleration of the surface layer analyzed by the equivalent linear model was greater than that from the nonlinear model for short distance and long distance earthquakes. The result in Figure 8 shows that the stress-strain value of the equivalent linear model of the soil was relatively greater than of the nonlinear soil model.

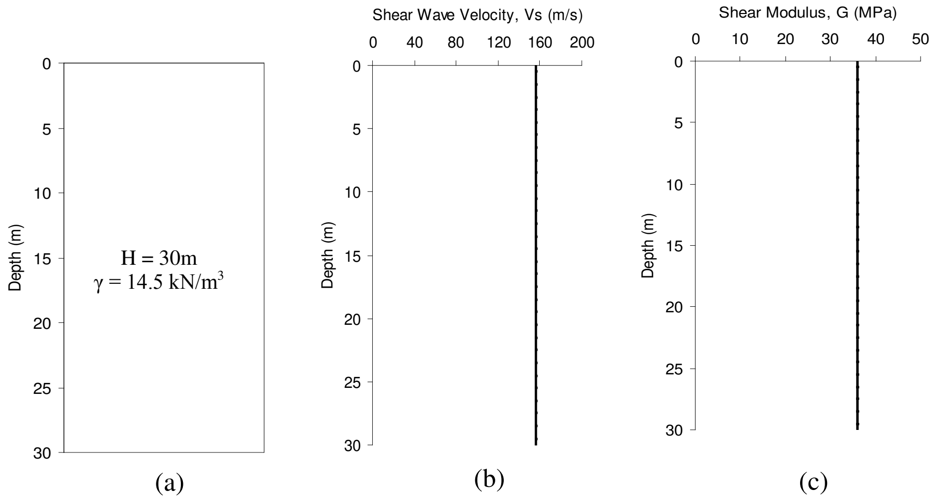

Figure 6 Soil profile: (a) physical properties; (b) shear wave velocity profiles; (c) shear modulus profiles.

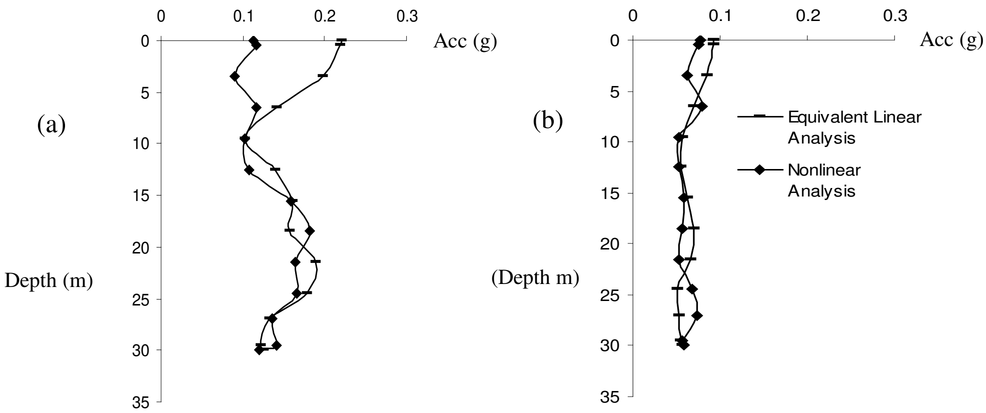

Figure 7 Comparison of acceleration-depth curves from equivalent linear analysis and nonlinear analysis: (a) short distance earthquake; (b) long distance earthquake.

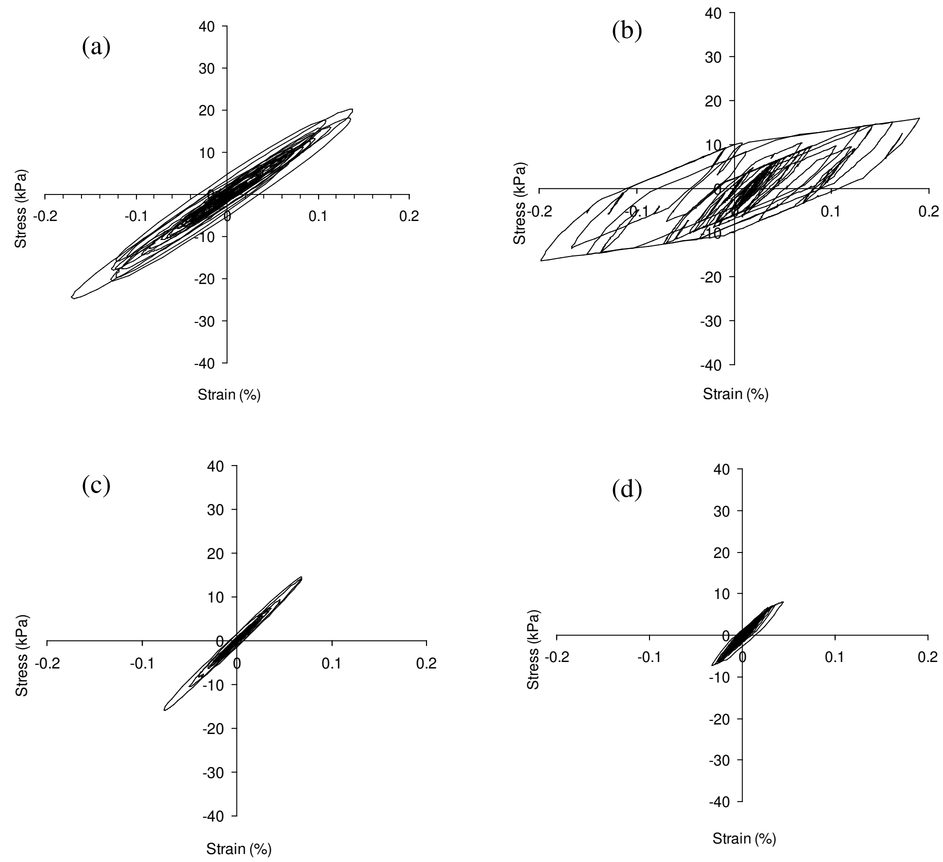

Figure 8 Stress-strain relation for Site Class E soil (loose sand): (a) equivalent linear soil model (short distance earthquake); (b) nonlinear soil model (short distance earthquake); (c) equivalent linear soil model (long distance earthquake); (d) nonlinear soil model (long distance earthquake).

3.2 The Case of Site Class D Soil (Homogeneous Dense Sand)

The Site Class D soil (homogeneous dense sand) profile represented in Figure 9 was analyzed using an equivalent linear soil and a nonlinear soil model. The input ground motion used had a maximum acceleration of 0.134 g for the short distance earthquake and 0.064 g for the long distance earthquake.

The results of the ground response analysis are shown in an acceleration-depth curve (Figure 10) and a stress-strain curve (Figure 11).

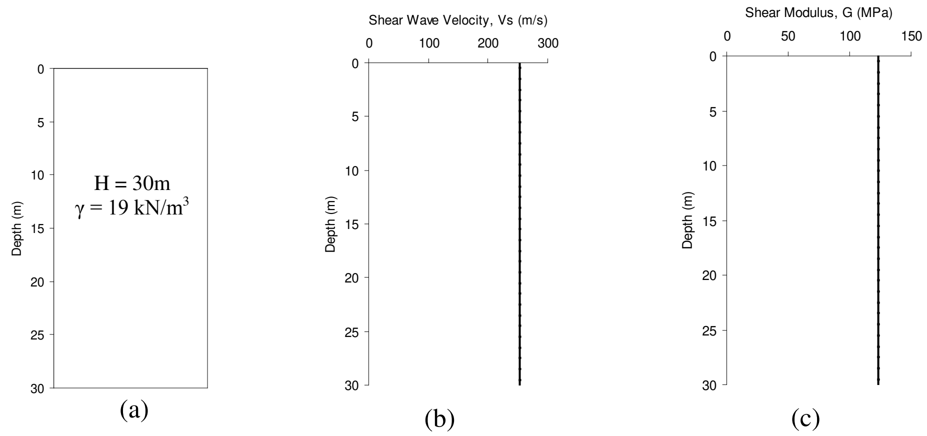

Figure 9 Soil profile: (a) physical properties; (b) shear wave velocity profiles; (c) shear modulus profiles.

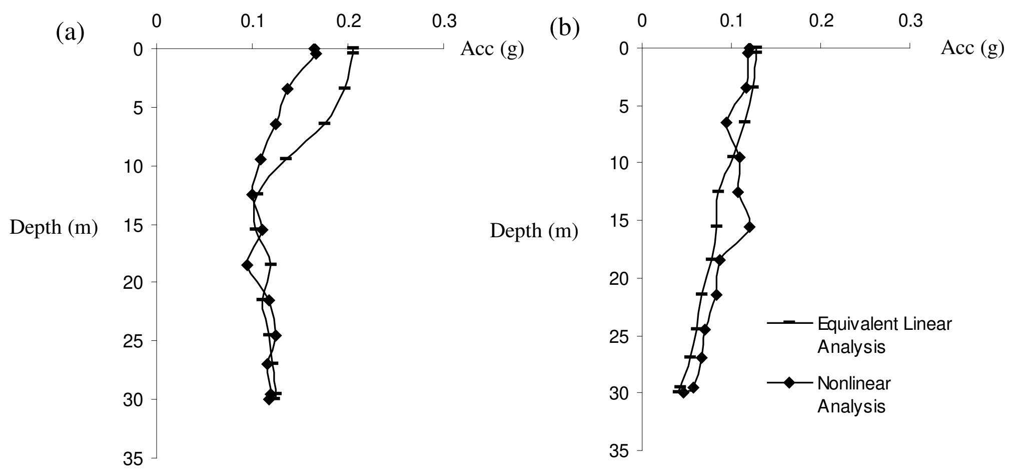

Figure 10 Comparison of acceleration-depth curves from equivalent linear analysis and nonlinear analysis: (a) short distance earthquake; b) long distance earthquake.

Figure 10 shows that the maximum acceleration value obtained from the equivalent linear soil model of the soil was relatively higher than that from the nonlinear soil model. Figure 11 also shows that the stress obtained from the equivalent linear model was relatively greater than that from the nonlinear soil model.

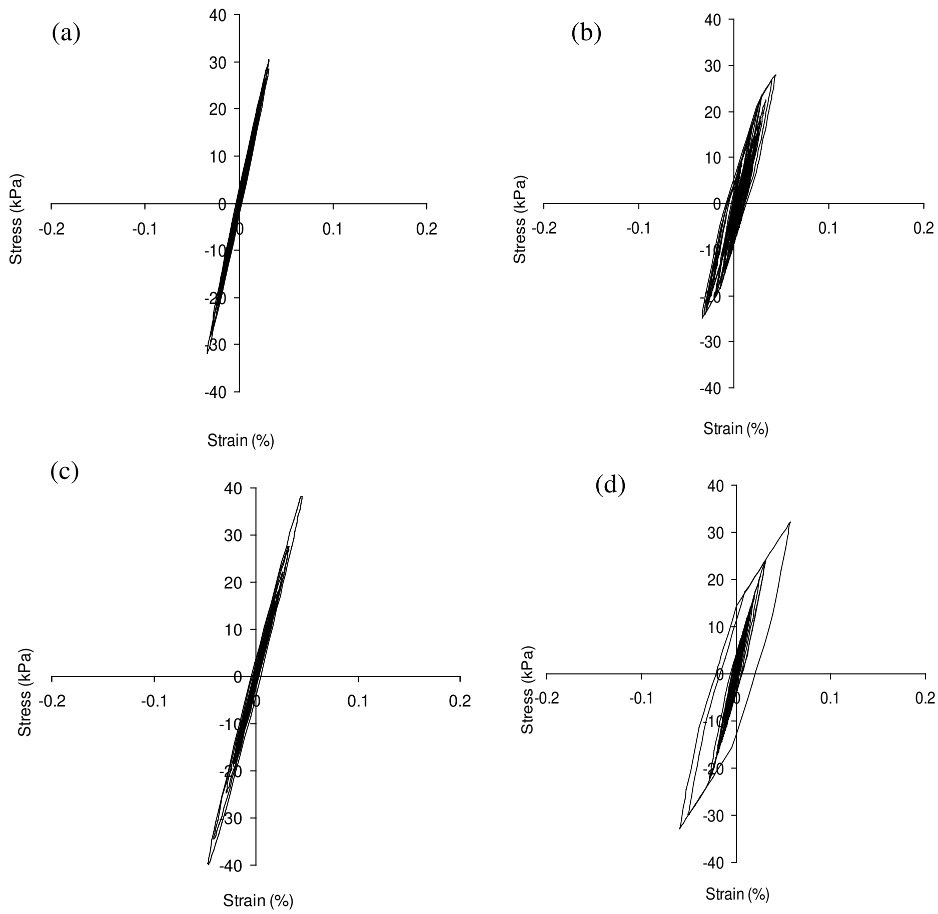

Figure 11 Stress-strain relation for Site Class D soil (dense sand): (a) equivalent linear soil model (short distance earthquake); (b) nonlinear soil model (short distance earthquake); (c) equivalent linear soil model (long distance earthquake); (d) nonlinear soil model (long distance earthquake).

3.3 The Case of Site Class E Soil (Homogeneous Soft Clay)

The Site Class E soil (homogeneous soft clay) profile represented in Figure 12 was analyzed using an equivalent linear soil model and a nonlinear soil model. The input ground motion used had a maximum acceleration of 0.134 g for the short distance earthquake and 0.064 g for the long distance earthquake. The results of the ground response analysis are shown in an acceleration-depth curve (Figure 13) and a stress-strain curve (Figure 14).

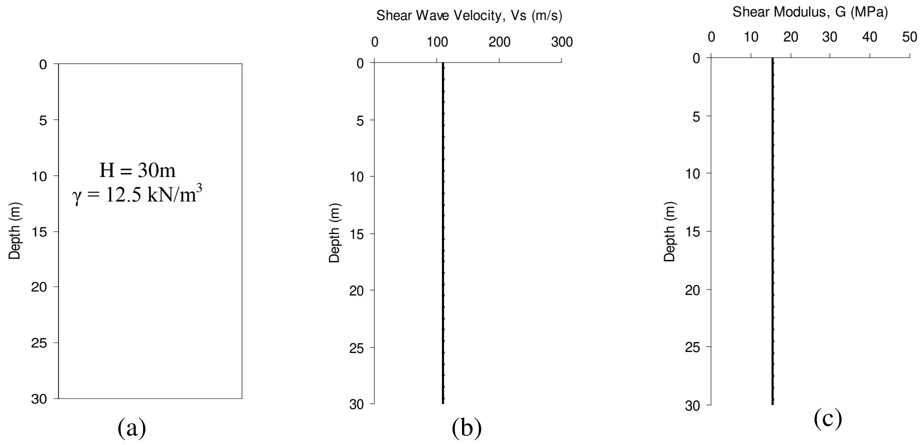

Figure 12 Soil profile: (a) physical properties; (b) shear wave velocity profiles; (c) shear odulus profiles.

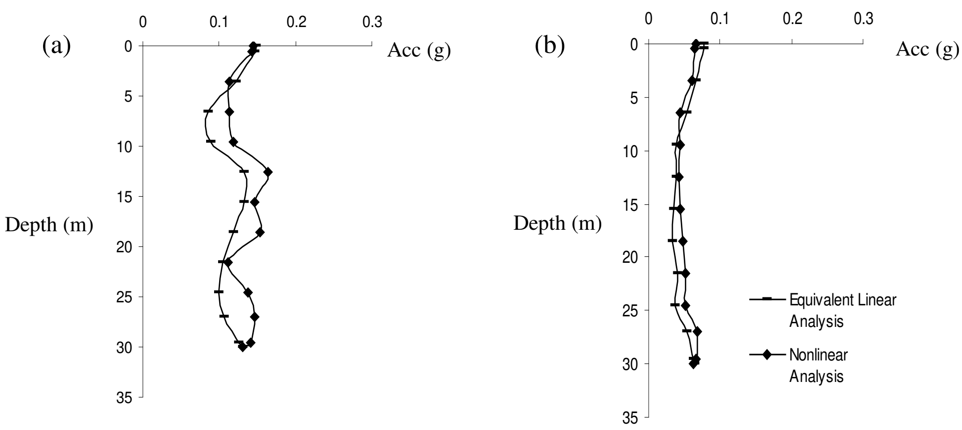

Figure 13 Comparison of acceleration-depth curves from equivalent linear analysis and nonlinear analysis: (a) short distance earthquake; b) long distance earthquake.

Figure 13 and Figure 14 show the results of the ground response analysis implemented on Site Class E soil (soft clay). The maximum acceleration value obtained from the equivalent linear model of the soil was almost the same as that from the nonlinear soil model. Figure 14 shows that the stress obtained from the equivalent linear model was relatively greater than that of the nonlinear soil model.

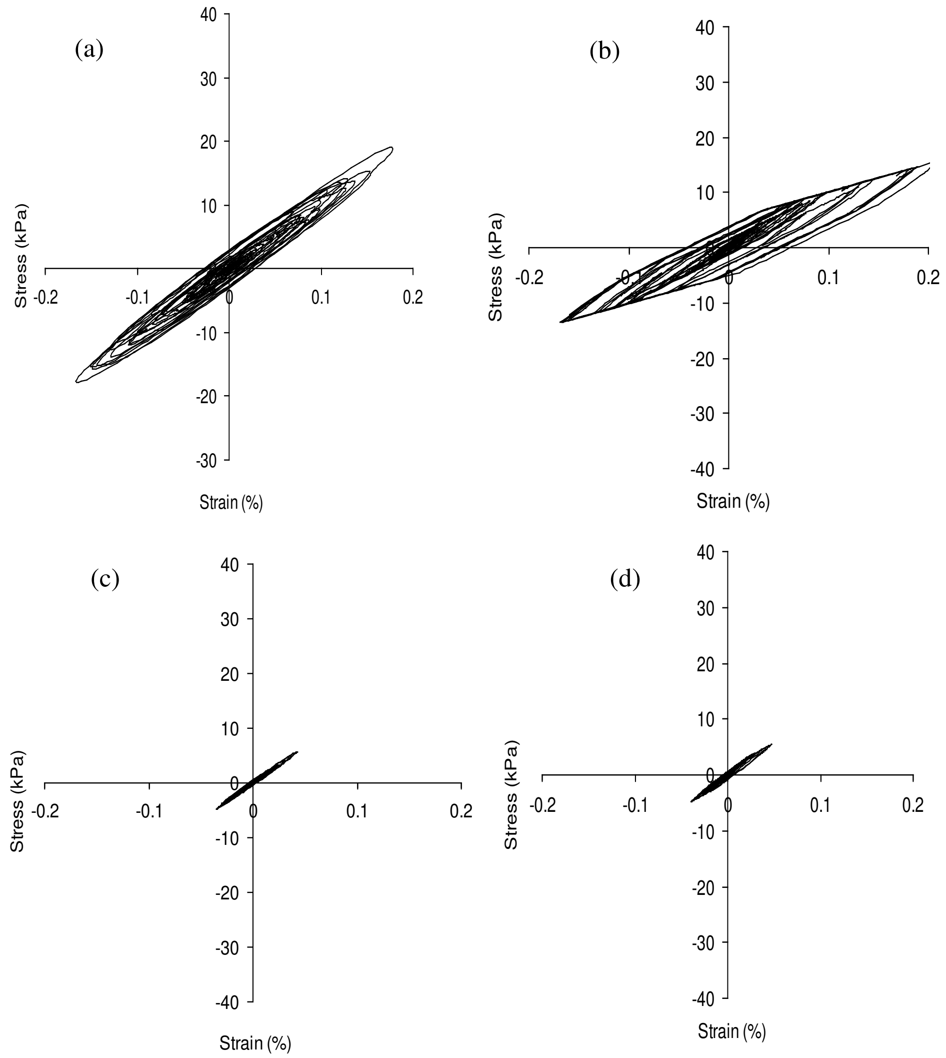

Figure 14 Stress-strain relation for Site Class E soil (soft clay): (a) equivalent linear soil model (short distance earthquake); (b) nonlinear soil model (short distance earthquake); (c) equivalent linear soil model (long distance earthquake); (d) nonlinear soil model (long distance earthquake).

3.4 The Case of Site Class D Soil (Homogeneous Stiff Clay)

The Site Class D soil (homogeneous stiff clay) profile represented in Figure 15 was analyzed using an equivalent linear soil model and a nonlinear soil model. The input ground motion used had a maximum acceleration of 0.134 g for the short distance earthquake and 0.064 g for the long distance earthquake.

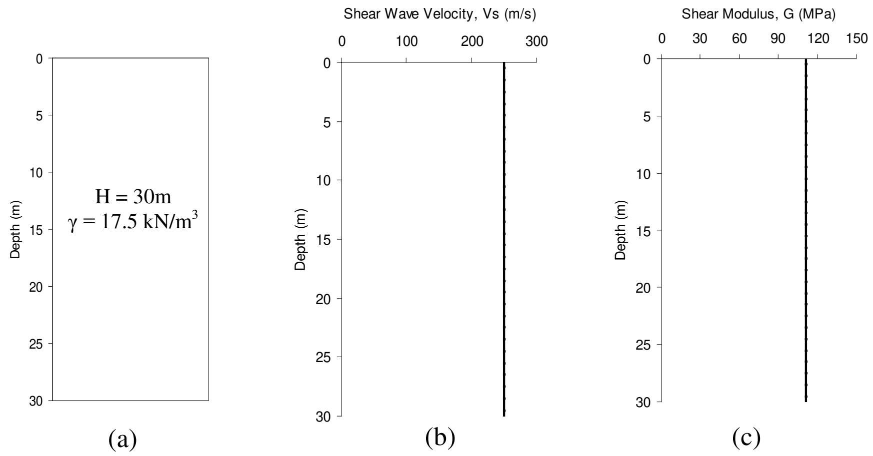

Figure 15 Soil profile: (a) physical properties; (b) shear wave velocity profiles; (c) shear modulus profiles.

The results of the ground response analysis are shown in an acceleration-depth curve (Figure 16) and a stress-strain curve (Figure 17). Figure 16 and 17 show the results of the ground response analysis performed on Site Class D soil (stiff clay).

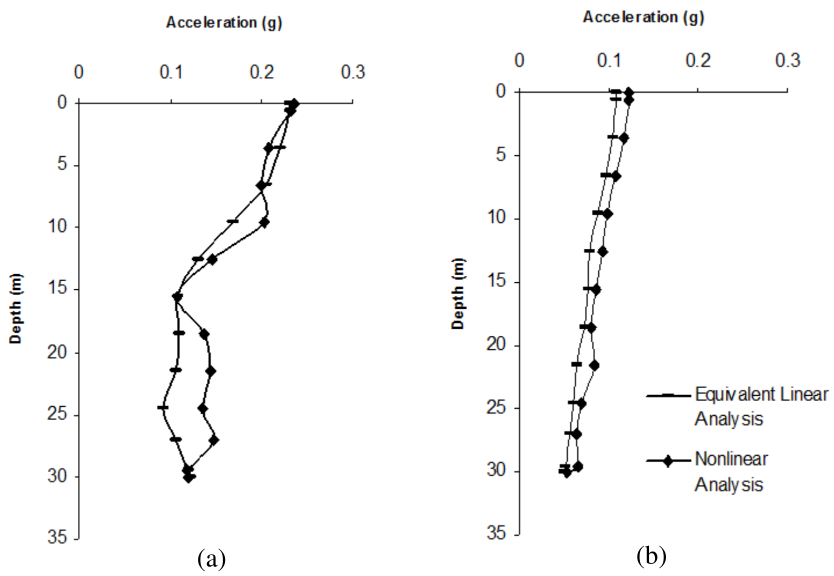

Figure 16 Comparison of acceleration-depth curves from equivalent linear analysis and nonlinear analysis: (a) short distance earthquake; b) long distance earthquake.

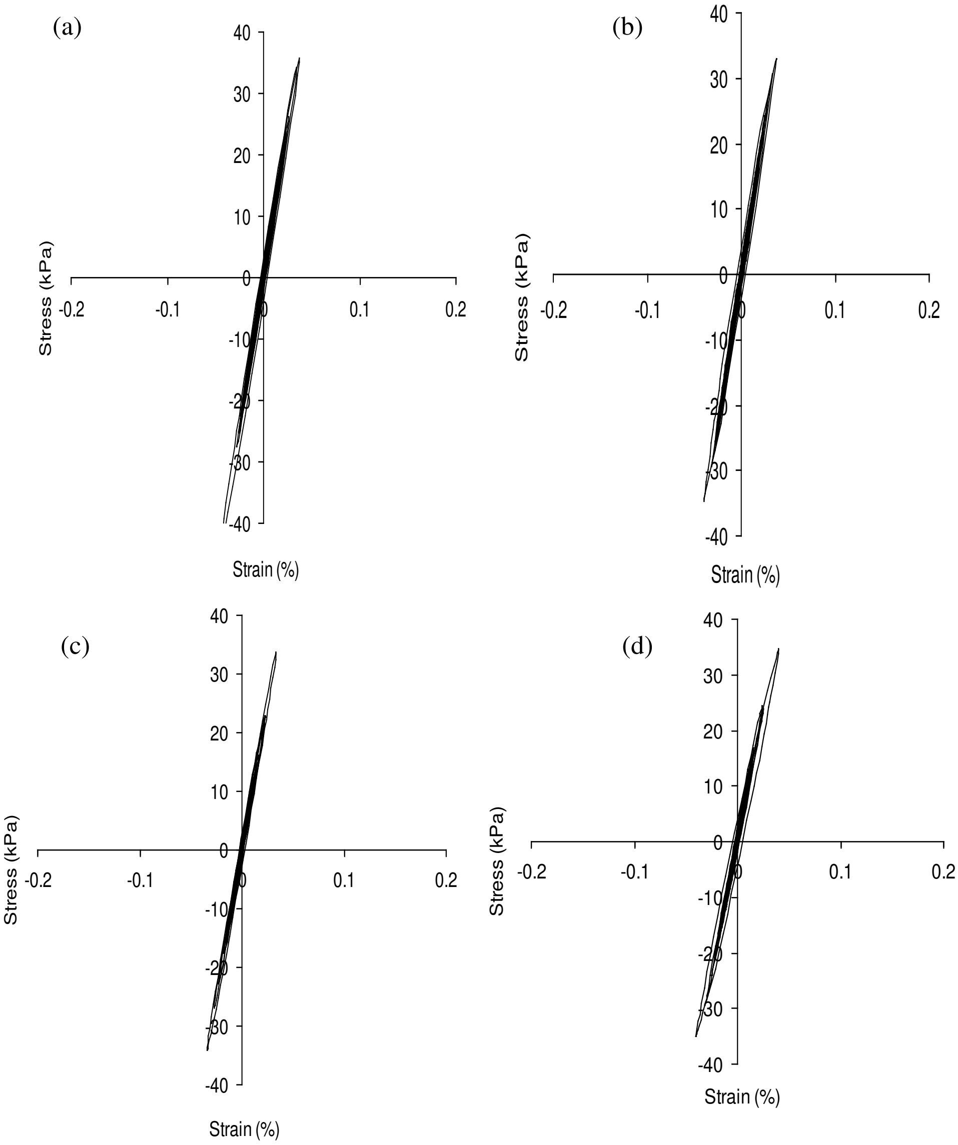

Figure 17 Stress-strain relations for Site Class D soil (stiff clay): (a) equivalent linear soil model (short distance earthquake); (b) nonlinear soil model (short distance earthquake); (c) equivalent linear soil model (long distance earthquake); (d) nonlinear soil model (long distance earthquake).

The stress obtained from the equivalent linear model was relatively greater than that from the nonlinear soil model. Figure 16 shows that the maximum acceleration value obtained from the equivalent linear model of the soil was relatively greater than that from the nonlinear soil model.

3.5 Variation of Peak Ground Acceleration

To highlight the response of the surface layer of soil, the peak ground acceleration of the short distance earthquake and the long distance earthquake were scaled up. The peak ground acceleration variations were 0.3 g, 0.4 g, 0.5 g, and 0.6 g, generating the peak surface accelerations in Figure 18 for Site Class E (loose sand and soft clay) and Site Class D (dense sand and stiff clay) soil respectively.

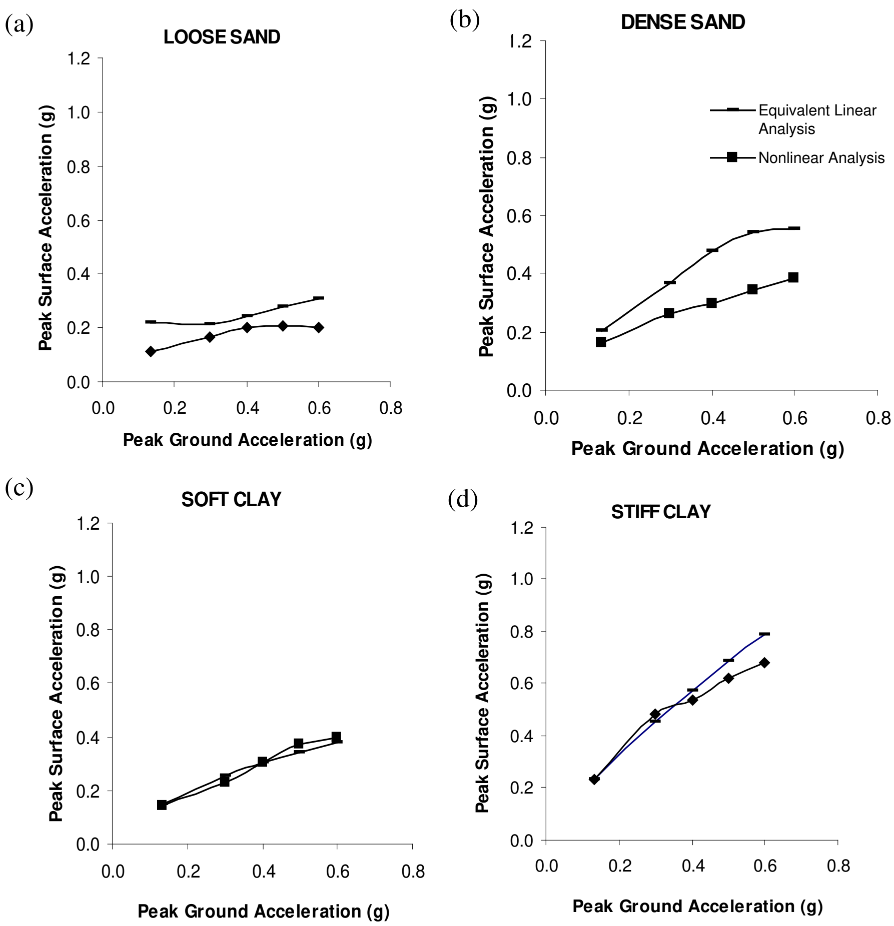

Figure 18 Peak surface accelerations obtained from peak ground acceleration for short distance earthquake: (a) loose sand, (b) dense sand, (c) soft clay, and (d) stiff clay.

Figure 18 shows that the value of the peak surface acceleration for the short distance earthquake obtained from the equivalent linear soil model was greater than that of the nonlinear soil model for loose sand, dense sand, and stiff clay. The value of the peak surface acceleration obtained from the equivalent linear soil model was the same as that from the nonlinear soil model for soft clay.

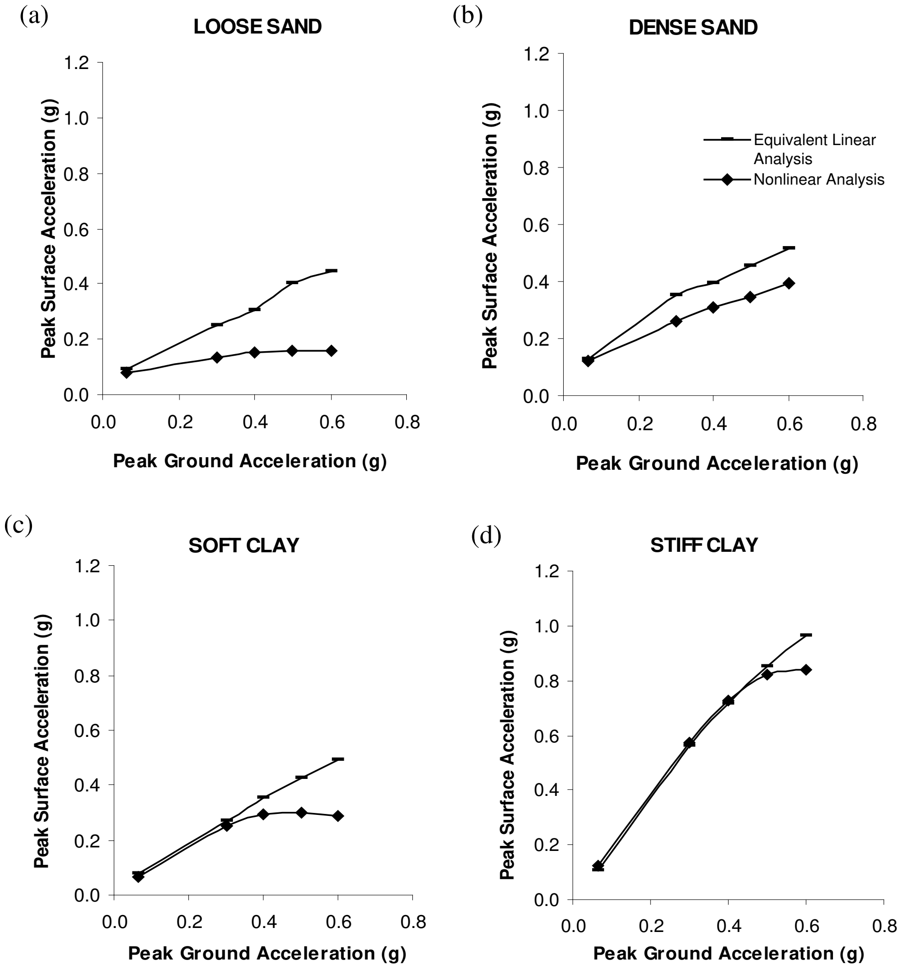

Figure 19 Peak surface accelerations obtained from peak ground acceleration for long distance earthquake: (a) loose sand, (b) dense sand, (c) soft clay, and (d) stiff clay.

Figure 19 shows the value of the peak surface acceleration for the long distance earthquake. It shows that the value of the peak surface acceleration obtained from the equivalent linear soil model was greater than that from the nonlinear soil model for loose sand, dense sand, soft clay, and stiff clay.

4 Discussion

To highlight the influence of the input motion on the seismic response of a soil layer, two earthquake signals were considered, i.e. the earthquake of Duzce (Turkey), a short distance earthquake, and the earthquake of Northridge, a long distance earthquake. These input motions were analyzed using an equivalent linear and a nonlinear soil model. The peak surface acceleration obtained from the equivalent linear soil model was greater than that from the nonlinear soil model for loose sand, dense sand, soft clay, and stiff clay for both the short distance earthquake and the long distance earthquake. For soft clay with a short distance earthquake, the value of the peak surface acceleration obtained from the equivalent linear soil model was the same as that from the nonlinear soil model.

The equivalent linear soil model for sand and clay (Site Class D and Site Class E soil) produced a constant shear modulus during the earthquake, both under a small and a big strain and could not show the change of stiffness that should occur during cyclic loading. In the nonlinear soil model, however, the soil modulus changed constantly depend on the strain. This is consistent with the nonlinear behavior of soil.

The nonlinear soil model showed inelastic behavior, in which the unloading path of the soil is different from the loading path, as shown in Figures 8(b), 11(b), 14(b), 16(b) for the short distance earthquake, and in Figures 8(d), 11(d), 14(d), 16(d) for the long distance earthquake.

This is consistent with the results of Miura, *et al.* [11], as shown in Figure 20.

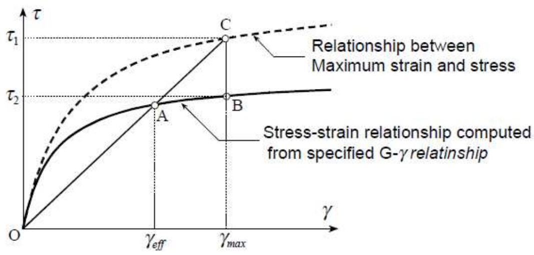

Figure 20 Schematic figure showing how the equivalent linear method overestimates shear stress (after Miura [12]).

Furthermore, Miura explained that the cause of this is that in the analysis of the equivalent linear soil model, the value of shear modulus (G) and damping ratio (ξ) used both result from the value of the effective strain, which is defined as $\gamma_{eff} = \alpha\ \gamma_{max}$, where γ_{max} is the maximum strain. The coefficient α is the coefficient of effective strain, which converts the maximum strain into effective strain. A value of $\alpha = 0.65$ is typically used.

5 Conclusion

The equivalent linear soil model for sand and clay (Site Class D and Site Class E soil) obtained a relatively greater value of stress-strain than the nonlinear soil model. The value of the peak surface acceleration obtained from the equivalent linear soil model was greater than that from the nonlinear soil model for loose sand, dense sand, soft clay, and stiff clay for both the short distance earthquake and the long distance earthquake. For soft clay with the short distance earthquake, however, the value of the peak surface acceleration obtained from the equivalent linear soil model was the same as that from the nonlinear soil model.

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